Project Proposal

High Dexterity Intraocular Manipulation

EN 601.656 Computer Integrated Surgery II

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Table of Contents

Clinical Motivation

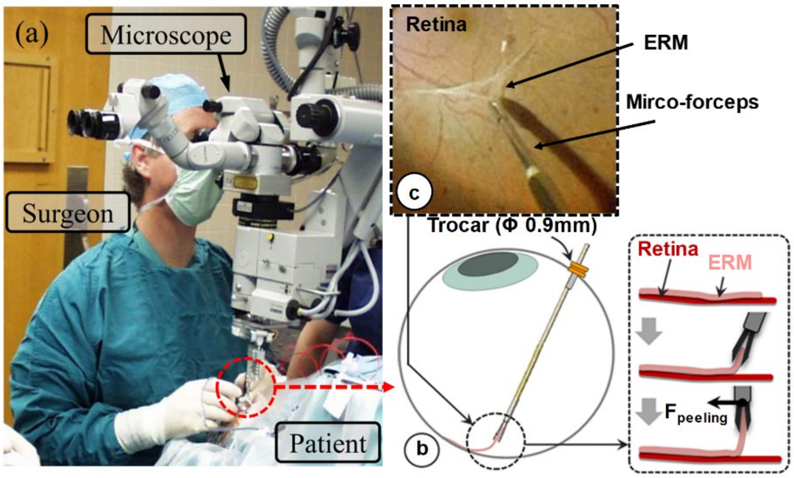


Figure 1: ERM peeling

Vitreoretinal surgery requires advanced surgical skills at or over the limit of surgeons' physiological capabilities. The surgery is performed in a confined intraocular space with restricted free motion of surgical tools. The forces exerted between the ophthalmic tools and eye tissue are often well below human sensory thresholds [1]. For instance, epiretinal membrane (ERM) peeling surgery shown in Figure 1, where a micron-scale membrane on the retinal surface is removed, requires the forces exerted by the surgeon to be less than 7.5 mN. And a force above the 7.5 mN could cause irreversible damage to the retina [2].

This project aims to move towards solving the clinical challenges mentioned above by providing the surgeons a cooperatively controlled robotic system with 2 DOF snake-like manipulator and a 5 DOF Steady Hand Eye Robot that has the capabilities of 1) tremor-free tool manipulation, 2) increased dexterity to ensure safe access to target from suitable directions, and 3) force sensing at the tool tip and sclerotomy.

Prior Work

This project will build upon prior work conducted by students and faculty at JHU. Key components include the Steady Hand Eye Robot (SHER), the Integrated Robotic Intraocular Snake (I^{2}RIS), and a multi-function force sensing and variable admittance control algorithm.

Steady Hand Eye Robot (SHER)

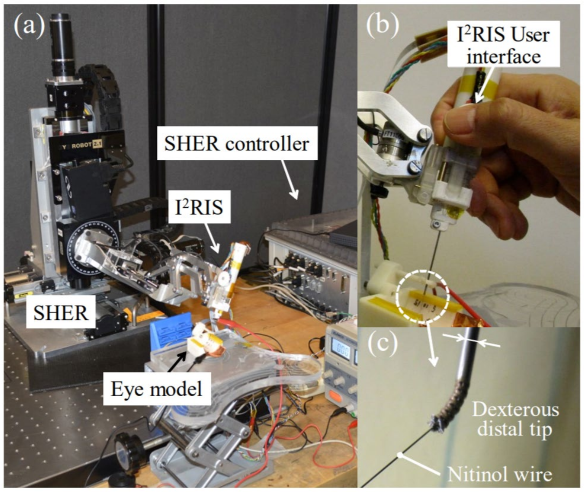


Figure 2: The integrated hardware with both SHER and I^{2}RIS and experiment setup.

The Steady Hand Eye Robot has five actuated Degrees of Freedom (DOF) and one passive DOF (tool rotation about tool axis), which are comprised of three translational DOFs (X,Y,Z) with linear stages and two rotational DOFs (roll and pitch), as shown in Figure 3 [3]. The robot is carefully designed with a mechanical RCM pitch mechanism so that surgeons can insert surgical tool into the intraocular space through sclerotomies (RCMs) and perform procedures including pitch and yaw motions of the tool without much movement at the sclera contact point which could cause tissue damage.

Integrated Robotic Intraocular Snake (I^{2}RIS)

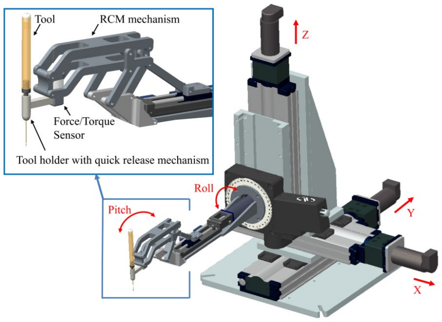


Figure 3: CAD model of SHER and 5 DOFs

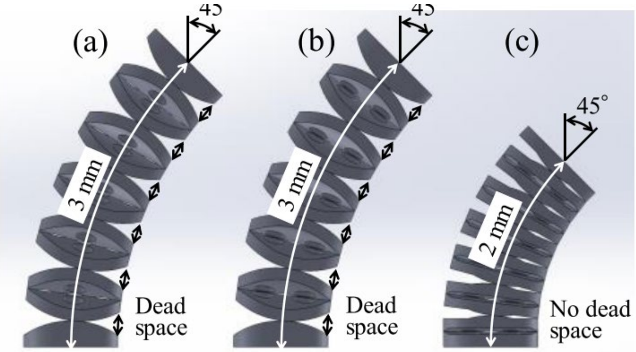


Figure 4: IRIS and I^{2}RIS: (a) conventional element, (b) conventional proposed element, (c) compact proposed element.

Several design iterations of intraocular snake robot have been developed and tested [1]. The most compact I^{2}RIS design, that we will base our project on is shown in Figure 4 (c). It has a diameter of 0.9 mm and a length of 2 mm with a ±45° bending motion range. And it will provide two DOFs (pitch and yaw) actuated by four wires on a drive pulley perpendicular to the actuation direction. The relationship between the control input, the rotation of drive pulley, and the control output, the bending angle of the snake-like distal end, was determined by geometric model and confirmed by experiments.

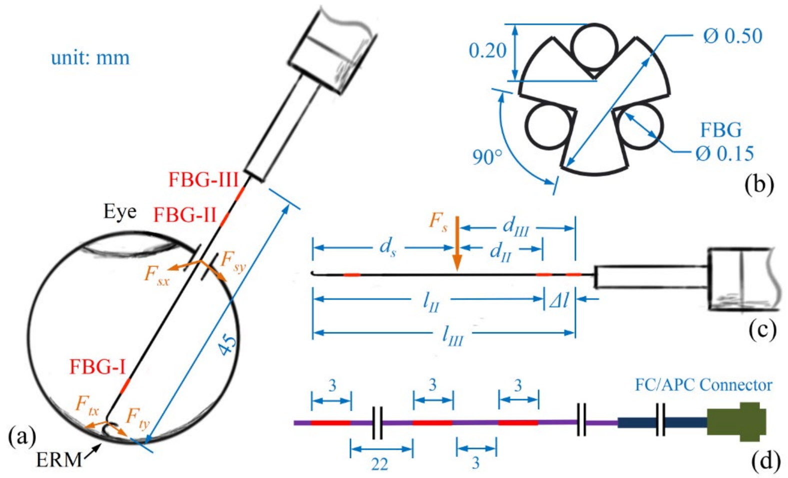


Figure 5: Tool shaft with FBG sensors

A multi-functional force sensing design was built using two sets of FBG segments, each with 3 FBG sensors [3]. The linear mapping from FBG sensor to forces applied was found from calibration experiments. Based on the assumption that the surgical tool is a rigid straight instrument when transversal forces are applied on tool tip and the shaft as Figure 4 shows, a force distribution model was established so that the forces at instrument tip and sclera and the sclera contact position can be calculated from FBG sensor readings.

A variable admittance control algorithm of SHER was designed to allow hand-over-hand control by the surgeon and to provide sclera force feedback to adapt to possible movement of the RCM point during surgeries [4].

Goals

It has been established that the I^2RIS and SHER systems are effective at positioning the end tool for robot-assisted Vitreoretinal surgery. However, the independent systems of control proved to be cumbersome in terms of actual use [1]. Additionally, the clinical motivation demonstrates that is both desirable and possibly necessary to have force constraints on the system, to reduce potential trauma on the patient. To these ends the follow goals were formulated to address the present issues:

- Cooperative control of the combined system.
- Tool tip follows a desired trajectory while maintaining force constraints (as deduced from FBG readings) on both the sclerotomy and tool tip.
- Surgeon controls the 7 DOF combined system with a 5 DOF Phantom Omni device.

Successful in achieving these goals would mean a surgeon would be able to conduct micro-surgery such as ERM peeling efficiently, without hand tremors, and with the confidence that the force being applied is within acceptable thresholds.

Technical Approach

Simulation

Simulation will be utilized in the development of the control algorithm, given the benefits of ease of access and risk mitigation. The robot system will be recreated in Gazebo, which allows for control via ROS nodes just like the real system. To create the meshes for a Gazebo simulation, the existing CAD files (Figure 6), in both Creo and SolidWorks formats, are converted to a neutral STEP format then into the OBJ format. To construct the segments of the distal end in the simulation, an invisible link will be used to connect two segments, with the link hinging at the center of invisible circles that are concentric to the segment curves (Figure 7). The amount of rotation will be constrained such that both sides are the same and the surfaces are effectively in non-slipping contact.

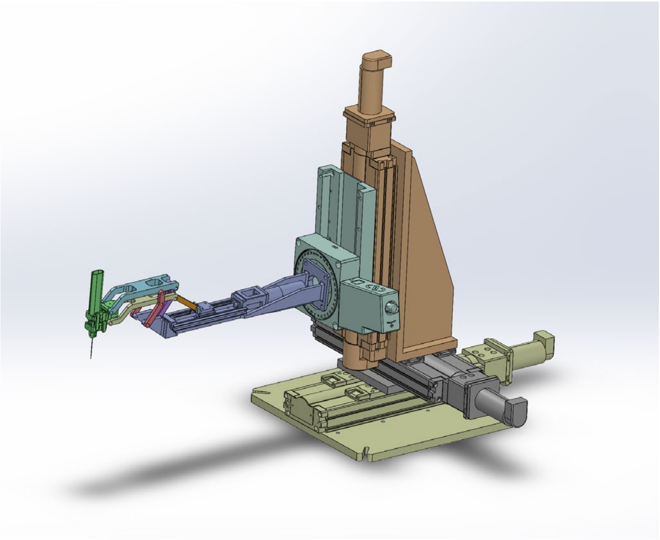


Figure 6: CAD model of integrated SHER and I^{2}RIS

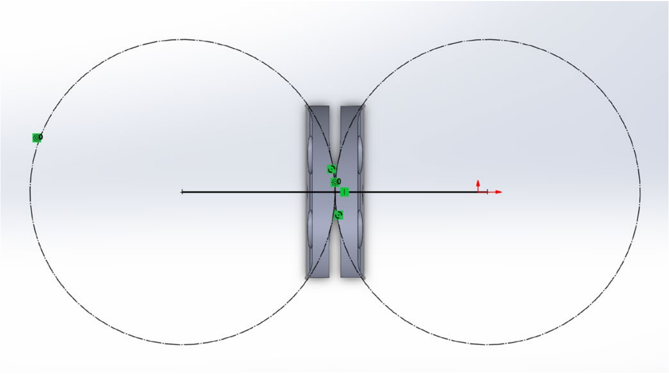


Figure 7: Representing segment interface as two non-slipping cylinders

Kinematics and force distribution analysis

Prior work focused on the control of SHER and improvement of snake robot, which were validated by experiments separately. Although they were assembled mechanically, the controls of them are kept separate. The force distribution model of the surgical tool was also based on the assumption that the FBG sensors are embedded on a rigid surgical tool with no bending. However, the tool tip force and sclera contact force should take into consideration the bending angle of the snake robot. And an integrated control of SHER and I^{2}RIS could further simplify the user interface by combining the control of SHER and I^{2}RIS, which also allows the surgery to be performed by the surgeon on a haptic device such as Phantom Omni.

Both the kinematics model and force distribution model of the system are needed to control the integrated system of SHER and I^{2}RIS. In this work, forward kinematics, inverse kinematics and Jacobeans of the integrated system will be calculated from existing kinematic model of SHER, geometric model of I^{2}RIS and CAD model that has measurements of the robot (shown in Figure 6). FEA on I^{2}RIS, with consideration of its pose, will be conducted to map the FBG sensor readings to tool tip force and sclera contact force. Calibration of the kinematics model and force distribution model will be performed to eliminate errors between real robot and CAD model.

Control algorithm

As mentioned above, SHER and I^{2}RIS are separately controlled. The surgeon needs to provide two different inputs (force and joystick/tactile switch) to the robots [2], which might complicate the user's experience of the integrated eye robot, especially when the tool is inserted into a restrictive intraocular space with limited, and risky, free movement of the tool.

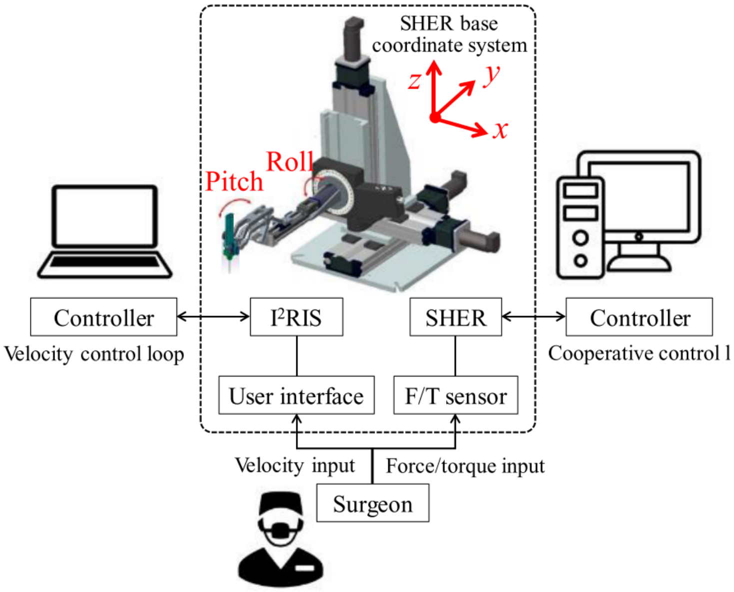


Figure 8: Control scheme of SHER and I^{2}RIS with separate inputs

In this work, we will design a constrained control algorithm that integrates the control of SHER and I^{2}RIS as shown in Figure 8. The hand-over-hand control of SHER will be employed until the surgical tool is inserted into the eye, at which point the integrated control algorithm takes over. The input provided by the surgeon along with the force information from FBG sensors control the pose, velocity and forces of the integrated eye robot. This control algorithm is key in keeping the tool tip force and sclera contact force within safe limits, which prevents irreversible damage during the surgery.

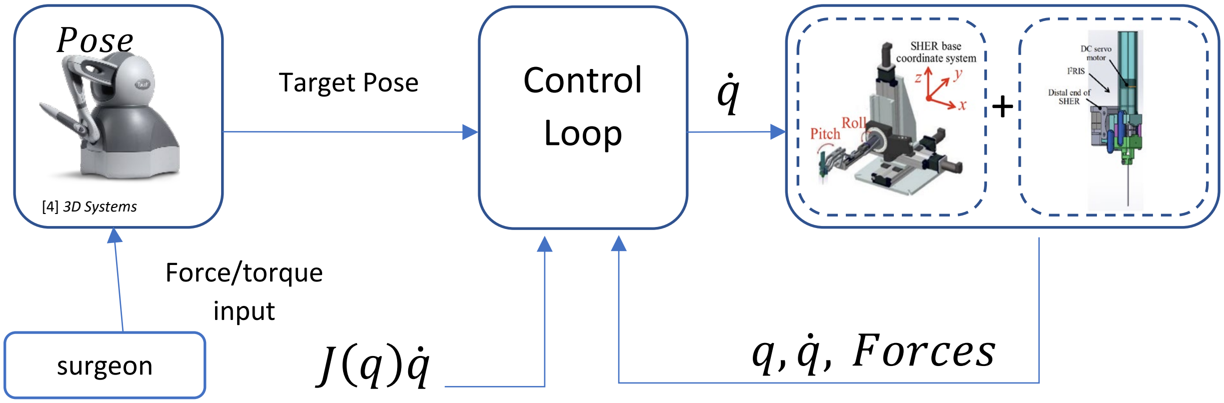


Figure 9: Proposed control scheme of integrated SHER and I^{2}RIS with one input

Software

CAD modeling will be done in SolidWorks. Kinematics modeling will be done in MATLAB. Simulation will be done with Gazebo in conduction with nodes running on the ROS (melodic) framework, to maintain compatibility with existing SHER ROS code.

Deliverables

Here is a table of deliverables that we will aim to deliver this semester. It is categorized into cumulative minimum/expected/maximum categories. At the minimum we aim to have the kinematic control model completed and the control algorithm planned out. We expect to have a fully functioning Gazebo simulation, with the control system implemented and tested. If everything goes according to the timeline, we also aim to demonstrate the control algorithm working with the real robots. Note that the implementation of the control system on real hardware will depend on the progress of embedding FBG sensors onto the I^{2}RIS, which is explained in the next section.

Table 1 Minimum, expected and maximum deliverables

	Deliverables	**Deadline**
Minimum	A report that includes calculation of forward kinematics, inverse kinematics, and Jacobean of the combined system	3/8
	A report on the force distribution analysis	3/15
	A schematic of the control algorithm design	3/29
Expected	A functioning gazebo simulation in which the end-effector of the simulated eye robot follow several optimized trajectories	4/5
	A report that summarizes the control algorithm, and an evaluation of the simulated system	5/5
Maximum	Implemented control system on real hardware	5/5
	Documentation of real world implementation	5/5

Dependencies

Table 2 Dependencies and contingency plan

Dependency	Status	Contingency	Followup	Funding	Deadline
SHER	Exists	Simulation	-	JHU Internal Funding	-
I^2RIS	No FBG force sensors	Only implement position control/FBG in simulation	Discuss with Prof. Iordachita	JHU Internal Funding	3/29
Computer running Linux for simulation	Exists	-	-	Personal computer	-
Phantom Omni	In lab	Joy-stick input/keyboard input	-	JHU Internal Funding	-

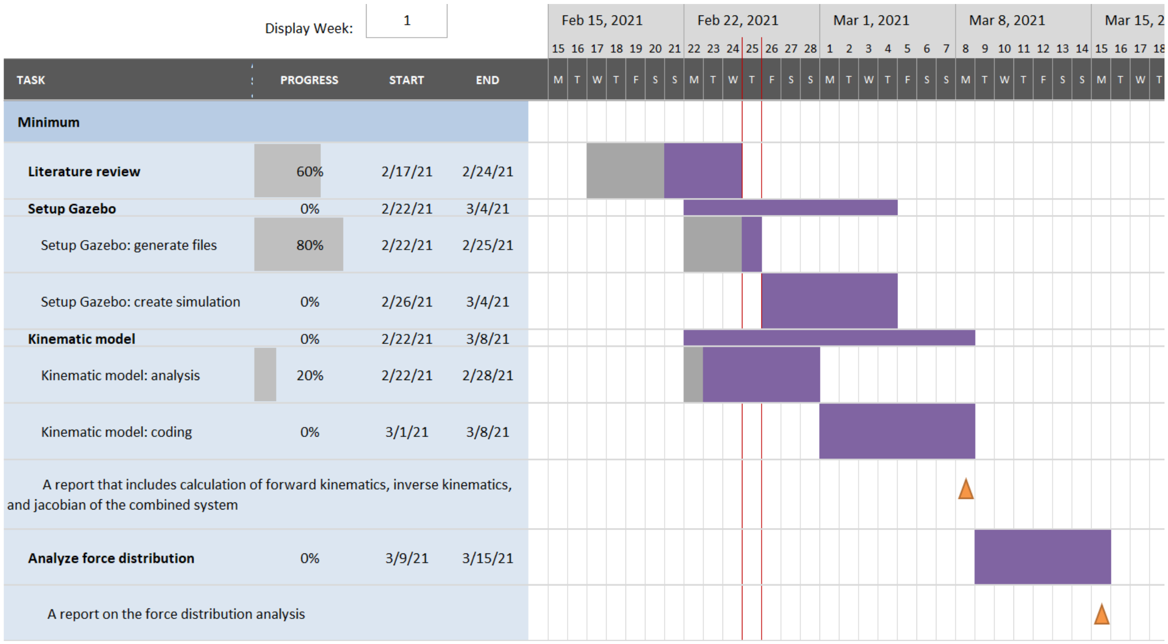
Most dependencies required for the project has already been acquired, except for the FBG force sensors that are not yet embedded on I^2RIS. We will discuss with Prof. Iordachita the plan and timeline for embedding FBG sensors. If we are not able to resolve this dependency, we will still be able to implement the robot control algorithm in simulation.

The contingencies represent the fall back plan if the dependency is no longer available/functioning. If the SHER is somehow not functioning, we will only implement in simulation, which would be the same as scaling back from our maximum deliverable to our expected deliverable. If the Phantom Omni is not available, we will simulate the same 5 DOF inputs with a joystick or keyboard.

Timeline and Milestones

An approximate timeline is proposed below with yellow triangles denoting due dates of deliverables, marking major milestones.

We hope to finish the minimum requirement of the project by early March, including the kinematic model, force distribution model and the setup of robot model in Gazebo.



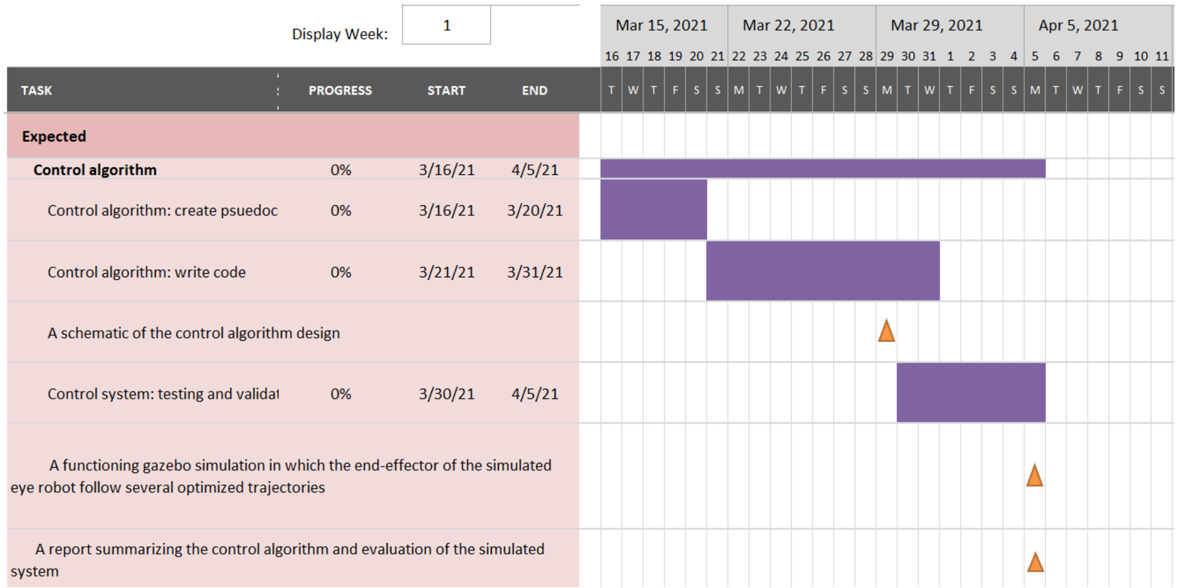
Display Week: 1

Feb 15, 2021 | Feb 22, 2021 | Mar 1, 2021 | Mar 8, 2021 | Mar 15, 2

TASK	PROGRESS	START	END
Minimum			
Literature review	60%	2/17/21	2/24/21
Setup Gazebo	0%	2/22/21	3/4/21
Setup Gazebo: generate files	80%	2/22/21	2/25/21
Setup Gazebo: create simulation	0%	2/26/21	3/4/21
Kinematic model	0%	2/22/21	3/8/21
Kinematic model: analysis	20%	2/22/21	2/28/21
Kinematic model: coding	0%	3/1/21	3/8/21
A report that includes calculation of forward kinematics, inverse kinematics, and jacobian of the combined system			
Analyze force distribution	0%	3/9/21	3/15/21
A report on the force distribution analysis			

Figure 10: Timeline with minimum deliverables

We expect to spend a considerable amount of time on control algorithm design and validation of the control algorithm. Expected deliverables will be finished by early April.



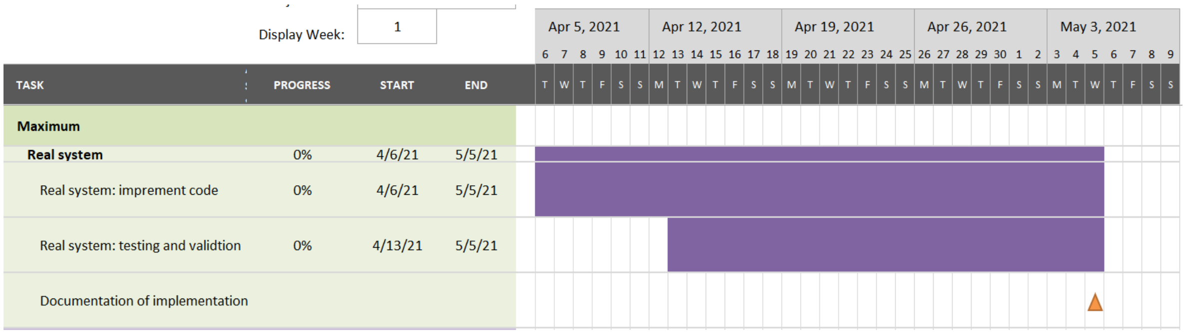
Display Week: 1

Mar 15, 2021 | Mar 22, 2021 | Mar 29, 2021 | Apr 5, 2021

TASK	PROGRESS	START	END
Expected			
Control algorithm	0%	3/16/21	4/5/21
Control algorithm: create psuedoc	0%	3/16/21	3/20/21
Control algorithm: write code	0%	3/21/21	3/31/21
A schematic of the control algorithm design			
Control system: testing and validat	0%	3/30/21	4/5/21
A functioning gazebo simulation in which the end-effector of the simulated eye robot follow several optimized trajectories			
A report summarizing the control algorithm and evaluation of the simulated system			

Figure 11: Timeline with expected progress

If we can resolve all dependencies, we will aim to successfully implement the control algorithm on the real eye robot system by the end of the semester.



TASK	PROGRESS	START	END
Maximum			
Real system	0%	4/6/21	5/5/21
Real system: imprement code	0%	4/6/21	5/5/21
Real system: testing and validtion	0%	4/13/21	5/5/21
Documentation of implementation			

Figure 12: Timeline of maximum deliverables

A complete timeline is shown below in Appendix

Team Makeup and Management Plan

The team consists of two members: Kaiyu Shi and Yishun Zhou. The team will be advised by mentors Professor Iulian Iordachita and Dr. Gang Li.

Due to the SARS-CoV-2 pandemic, it is not possible to conduct regular in-person meetings for the project. Communication between team members will be facilitated by Slack, with file and code sharing conducted via OneDrive and private GitHub repository, respectively. Communication between the team and mentors will be conducted over email, along with a weekly zoom session for updates and in-depth discussions.

Reading List

Jinno, Makoto, and Iulian Iordachita. “Improved Integrated Robotic Intraocular Snake*.” *2020 International Symposium on Medical Robotics (ISMR)*, 2020, doi:10.1109/ismr48331.2020.9312927.

He, Xingchi. *Force Sensing Augmented Robotic Assistance for Retinal Microsurgery.* 2015. Johns Hopkins U, PhD dissertation.

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[1] Jinno, Makoto, and Iulian Iordachita. “Improved Integrated Robotic Intraocular Snake*.” *2020 International Symposium on Medical Robotics (ISMR)*, 2020, doi:10.1109/ismr48331.2020.9312927.

[2] P. Gupta, P. Jensen, and E. de Juan, “Surgical forces and tactile perception during retinal microsurgery,” in *International Conference on Medical Image Computing and Computer Assisted Intervention*, vol. 1679, 1999, pp. 1218–1225

[3] Makoto Jinno, Gang Li, Niravkumar Patel, Iulian Iordachita, “An Integrated High-dexterity Cooperative Robotic Assistant for Intraocular Micromanipulation”, 2021., Kokushikan University

[4] He, Xingchi. Force Sensing Augmented Robotic Assistance for Retinal Microsurgery. 2015. Johns Hopkins U, PhD dissertation.

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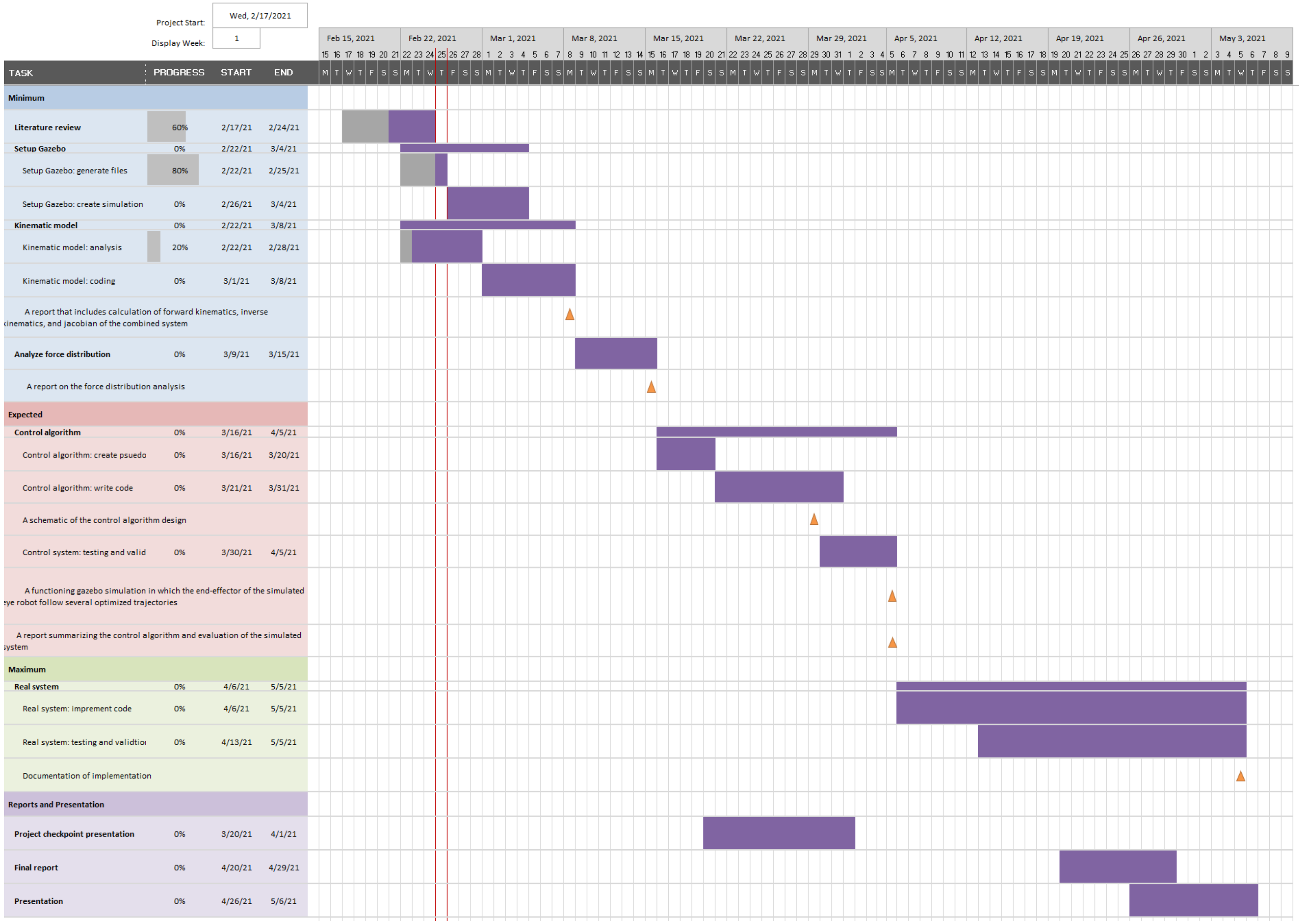
[6] Üneri, Ali, Marcin A. Balicki, James Handa, Peter Gehlbach, Russell H. Taylor, and Iulian Iordachita. "New steady-hand eye robot with micro-force sensing for vitreoretinal surgery." In 2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 814-819. IEEE, 2010.

Appendix



Project Start: Wed, 2/17/2021

Display Week: 1

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Real system: imprement code	0%	4/6/21	5/5/21
Real system: testing and validtioı	0%	4/13/21	5/5/21
Documentation of implementation			
Reports and Presentation			
Project checkpoint presentation	0%	3/20/21	4/1/21
Final report	0%	4/20/21	4/29/21
Presentation	0%	4/26/21	5/6/21